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Tides and Circulation in a Series of Saline Lakes at Christmas Island[1]

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ABSTRACT: Hydrographic conditions are presented for a series of seven saline lakes which open off of the main lagoon at Christmas Island, and which are being considered as a potential aquaculture site for brine shrimp. The first five ponds have typical tidal ranges of 1 foot and residence times of about 11 days. The two ponds farthest inland are penetrated only by spring tides and have residence times in the order of 15 months. The tides themselves, as well as mean water-level and tidal phase differences, present several possibilities for producing a controlled flow through the ponds. Circulation and structure in one of the innermost ponds show that no significant nutrient traps exist, and that flow patterns would serve to help collect floating brine shrimp eggs.

AT CHRISTMAS ISLAND, much of the original atoll lagoon has been rendered dry land—apparently by a sequence of erosion, reef-building, and sedimentation that accompanied sea level changes and a possible, recent northwestward tilting of the atoll (Wiens, 1962). Past reef growth within the lagoon followed a somewhat rectilinear, interconnecting pattern that probably established the geometry present today in the form of the many ridges which enclose dry basins, isolated ponds, and lakes intercommunicating through relatively narrow channels. Other stages of a similar topographic development seem to be present elsewhere in the Line Islands. Jarvis Atoll has a filled lagoon, and the lagoon at Fanning Island is honeycombed by interconnecting line reefs. Christmas Island may represent an intermediate stage. About half of the atoll is now above water, and another fourth of its surface area (about 160 km^2) is covered by saline lakes and ponds. These extensive interior water bodies are a unique feature among the world's atolls.

The saline lakes and ponds are not currently used by man, but there is an idea that some of them might be suitable for aquaculture. This could provide a new local industry to help the economy of the Gilbert and Ellice Islands (and presumably better the people's living standards, if population growth can be kept from wiping out the economic advance). The culture of brine shrimp (*Artemia*) might be especially suitable for the lakes, since it requires moving the organisms through a series of enclosures of increasing salinity to cause egg production. To investigate the feasibility of such a project, a team from the University of Hawaii went to Christmas Island in November 1971 to survey the physical and biological conditions in one set of seven lakes which branch off from the main lagoon in a sequential series. This paper presents the hydrographic findings. Water levels, winds, water temperatures, and currents were measured to determine flushing rates through the pond series, circulation patterns within a single pond, and the potential uses or difficulties these might present in an aquaculture operation.

TIDES

Water levels in the ponds were studied for the purpose of answering four questions:

1. What are the existing flushing rates or residence times of water in each pond?
2. If the tides were used to produce a net circulation through the pond series, what volumes of flow could be expected?
3. Are there naturally occurring tidal phase

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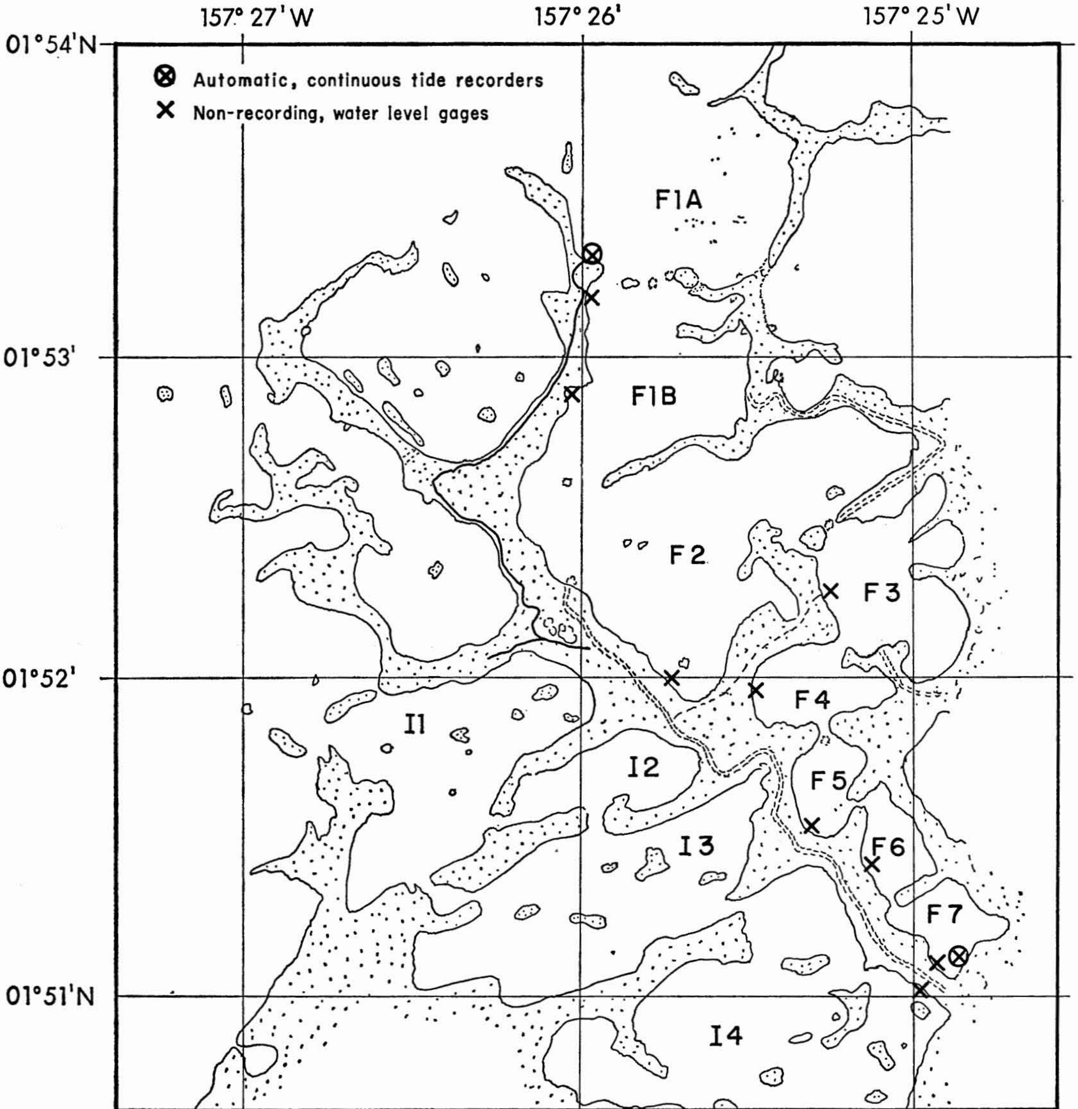

FIG. 1. Map of F-pond series and adjacent areas, showing tide measurement locations.

differences between ponds that could be used to promote net flows?

4. Are there mean-water-level differences between ponds that could be used to promote net flows?

Water levels were measured in each lake at the locations shown in Fig. 1. Readings were taken every hour from 1100 (local time), 8 November 1971 to 2000, 10 November 1971. During the same period, hourly readings were taken of wind velocity and surface water temperature in lake F1B. The relative elevations of all gages shown in Fig. 1 were determined by survey so that differences in mean water level between ponds could be computed.

The tide records will be discussed starting with the outermost pond, which is the one most directly connected with the main lagoon, and moving landward through the series, passing toward ponds that are sequentially farther removed from the lagoon.

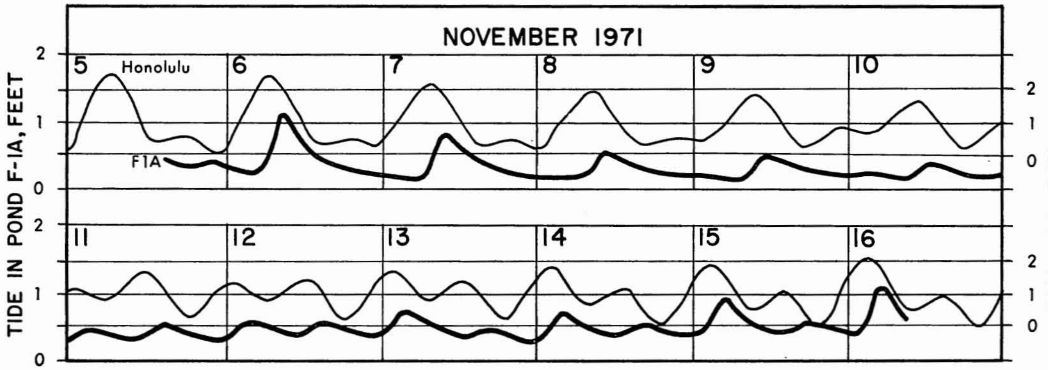

Fig. 2. Recorded tide in pond FIA. Honolulu tide shown for comparison.

Tides in the Main Lagoon

The tide in the outermost pond, F1A, may be taken to represent the tide in the neighboring region of the main lagoon. F1A does not open immediately to the main lagoon, but we note that wherever the lakes are interconnected by fairly wide passages there is negligible distortion of the tide wave over short distances. This shows clearly in the similarity of the records from F1A and I4, which are connected via the main lagoon. Thus we regard the record from F1A as the tide in the local, inner portion of the main lagoon. This tide is shown in Fig. 2. The range is about 1 foot, and the form of the wave is strongly distorted.

Tides measured in the inner end of the lagoon do not necessarily represent conditions throughout the whole lagoon. When a large lagoon has limited communication with the surrounding ocean, the tide in the inner parts of the lagoon will lag that close to the atoll inlets. The delay can be more than an hour. Such delays are found at Fanning Island (Gallagher et al., 1971) and are very likely to be present here. The tide is routinely recorded in the lagoon at London (near Cook Inlet), and relatively simple empirical formulas could be derived to give the tide in the inner lagoon from the London measurements.

The distortion of the lagoon tide is interesting to note. The water rises quickly and recedes slowly, with the crest shifted forward in time—a pattern that characterizes nonlinear distortion of the wave. In general there are two processes that can produce nonlinear distortion of a tide: passage of the wave through extensive regions of shallow water, and bottom friction (Gallagher and Munk, 1971). Although both processes are undoubtedly present in the lagoon, the shape of the wave indicates that the first is predominant here. The lagoon is large enough so that a nondistorted tide entering from the open ocean will undergo a shoaling transformation, becoming steeper in front somewhat like an ordinary swell wave approaching a beach. (A good example of frictional distortion appears inside the pond series and will be discussed later.) The nonlinear distortion of the lagoon tide at Christmas Island is very pronounced; the island would be an excellent place to conduct field studies of this phenomenon.

There is some practical motivation in seeing whether the Christmas Island lagoon tide bears any predictable relation to the Honolulu tide. Both curves, therefore, are given in Fig. 2. There is no simple relation which would give accurate lagoon predictions based on Honolulu. However, rough estimates could be made: the lagoon tide has somewhat less than half the Honolulu amplitude, high water lagging by about 2 hours and low by about 5 hours.

Tides in the F-Pond Series

A set of hourly water level readings through the pond series is presented in Fig. 3. Tides in the outer lakes, through F4, follow the local lagoon tide with little if any discernible differences. This is simply because these ponds are

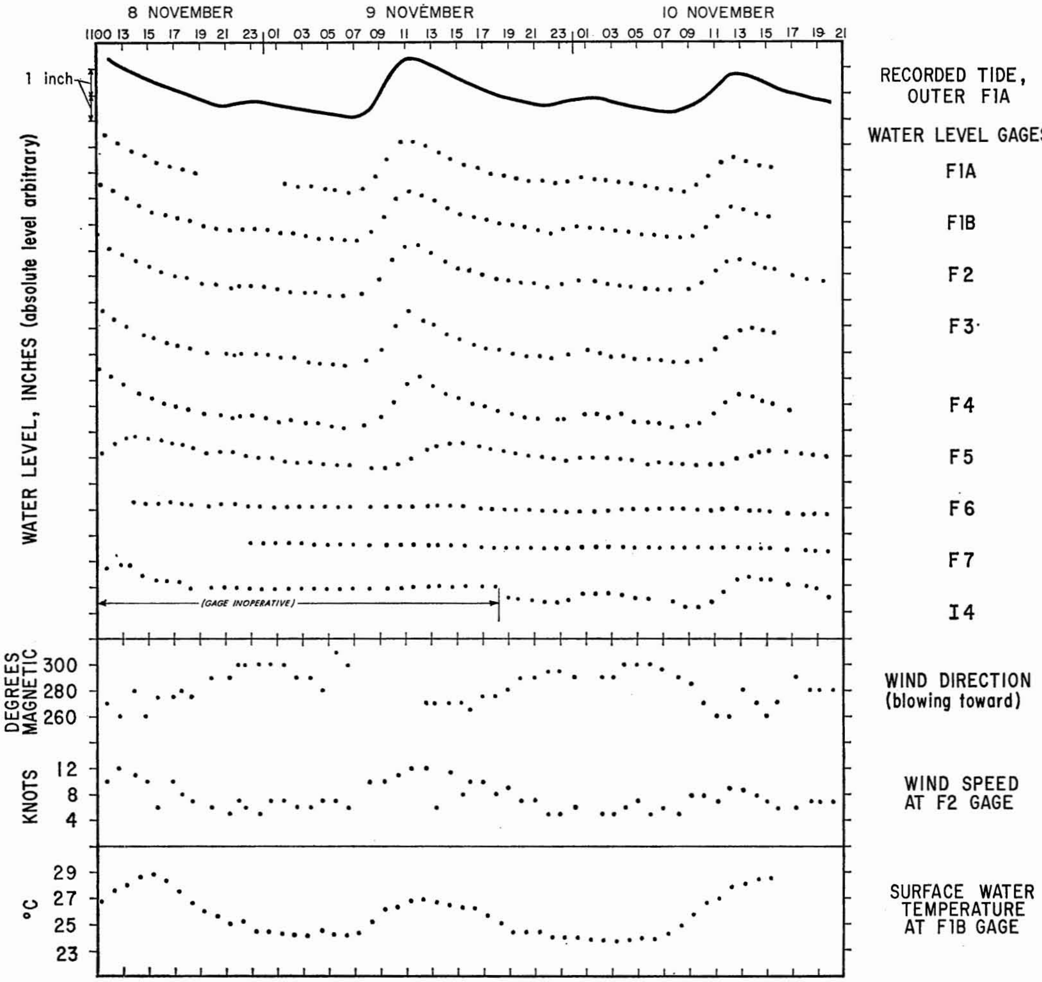

FIG. 3. Water levels, wind speed and direction, and surface water temperature measured in and near the F-pond series.

connected by relatively large passes which permit appreciable volume flow.

The first noteworthy tidal difference occurs between F4 and F5. These ponds are connected by a shoal pass about 1 foot deep and in the order of 25 feet wide which impedes the tidal flow. The impedance displays the character of a nonlinear frictional process. High tides in F5 are reduced in amplitude by as much as a factor of two and may lag those in F4 by as much as 2 hours. The nonlinearity of the channel resistance enhances these effects (amplitude reduction and phase delay) on the larger tides. The tidal phase difference between F4 and F5 could be used for limited practical purposes, and this will be discussed later.

The channels connecting F5 with F6, and F6 and F7 are less than 20 feet wide and less than 1 foot deep. In fact, the sills of these channels lie above the mean water level of F5, so that only the higher tides penetrate into F6 and F7. These penetrations do not cause normal tides in F6 and F7; they are simply additions of water which tend to replace what has evaporated. Such additions did not occur during our period of hourly monitoring, and the curves in Fig. 3 show an evaporation rate of about 0.5 inch per day. From the evaporation rate, the height

TABLE 1

RESIDENCE TIMES IN PONDS F1–F5

POND	VOLUME (FT^3)	% OF POND VOLUME EXCHANGED PER DAY	RESIDENCE TIME (DAYS)
F1A	189×10^6	8.8	11.4
F1B	154×10^6	8.8	11.4
F2	274×10^6	8.8	11.4
F3	105×10^6	8.8	11.4
F4	42×10^6	8.8	11.4
F5	30×10^6	4.5	22.2

TABLE 2

RESIDENCE TIMES IN PONDS F6 AND F7

POND	VOLUME (FT^3)	% OF POND VOLUME EXCHANGED PER MONTH	RESIDENCE TIME (MONTHS)
F6	27×10^6	6.7	15
F7	32×10^6	6.7	15

of the tide in F5, and the measured difference in mean water levels between F5 and F6, it can be concluded that the occasional penetrations of water from F5 must occur at least as often as once a month. It cannot be proved with this set of measurements, but it seems highly probable that the penetrations occur diurnally during spring tides, happening 3 to 6 days in a row about every 2 weeks.

There are tidally driven changes in the height of the water table at Christmas Island. The possibility arises that this has some effect on the tides observed in the ponds, but it seems quite unlikely for several reasons. The water-table fluctuations are damped out with increasing distance from the coast; their amplitudes have already decreased by about a factor of two at a point 500 meters inland, where they are of order 10 cm (Jenkin and Foale, 1968). One would expect the fluctuations to be even smaller beneath the F-Ponds, about 5 km inland. The actual records show no sign of any influence from water-table fluctuations. The amplitudes and phases of the observed tides are consistent with their being driven only by water flows through the channels interconnecting the ponds and the main lagoon. And when the channel flows ceased in F6 and F7, no water level fluctuations were discernible. It is concluded that water-table tides are not influencing the tides seen in the F-Ponds.

Volume Exchanges and Residence Times

Residence times and daily percentage volume exchanges are tabulated in Table 1 for the ponds which have normal tidal fishing. For the computations, a mean depth of 15 feet was taken for all ponds, and pond areas were planimetered from a map based on aerial photos. Residence time is computed as the volume of the pond divided by the tidal volume-exchange rate. If a pond were perfectly mixed at all times, then on the average a water parcel would stay in the pond for the residence time. Since the ponds are probably not perfectly mixed in reality, the computed residence times should be treated as minimum values.

Ponds F6 and F7 do not have normal tidal exchange and must be treated differently. Volume exchange has been calculated for the observed cycle of evaporation and occasional refilling. The numbers in Table 2 refer to water but not to dissolved substances.

Mean Water Level in the Pond Series

Mean water level for each pond is listed in Table 3, where the elevation in F1A has been used as an arbitrary zero level. Errors in the level survey and in the tide readings could amount to about ± 0.05 feet. Thus to within the limits of measurement accuracy, mean water level is constant throughout the outer ponds—as would be anticipated from their free communication with the lagoon tide. Note that I4, which lies adjacent to the most landward F-ponds, is in good communication with the main lagoon and shares the same water level.

Unlike the other table entries, the water levels listed for F6 and F7 do not represent steady, average values. As mentioned before, water is added to these ponds only during spring tides; the rest of the time their levels are falling due to evaporation at the rate of about 0.50 inch per day. (In the rainy months of January–May, the average net rate of evapora-

TABLE 3

MEAN WATER LEVELS

POND	MEAN WATER LEVEL (FT)
F1A	0.00
F1B	0.01
F2	−0.04
F3	−0.05
F4	−0.04
F5	−0.05
F6	−0.64 (on 9 November)
F7	−0.65 (on 9 November)
I4	0.00

tion over precipitation would be reduced to about 0.25 inch per day.) At the time of our hourly monitoring, F6 and F7 stood about 0.65 foot below the mean water level in the outer ponds. Their monthly or semimonthly range of water level is probably between 6 and 12 inches. Most, or perhaps even all, of the time, F6 and F7 stand below the mean water level in F5 and I4—a fact which could be used in a system of flow control.

TEMPERATURE AND WIND

Surface water temperature and wind velocity were observed hourly during the period 8–10 November, and the data are presented in Fig. 3. Surface temperature in pond F1B undergoes a diurnal cycle, peaking near midday with a range of about 5° C. Since no tidal effects are seen, this curve is probably typical of most of the outer ponds in the series. A similar range could be expected in F6 and F7, but the actual temperatures would probably be higher.

The Southeast Trades are present almost constantly at Christmas Island. (The resident plantation manager could recall only 2 or 3 calm days in the past 3 years.) During the measurement period the wind showed a clear diurnal pattern: strengthening to about 12 knots at midday and dying off to 5 knots during the night. Wind direction was also diurnal; the lighter wind blew toward about 260° magnetic and shifted to 300° as it grew stronger. The winds produced no measured water level changes in the ponds, except in F6 and F7 where, during the midday hours when wind velocity is maximum, there is about 0.5 inch of set-up at the leeward sides of the ponds. This effect can be seen in Fig. 3.

POSSIBILITIES FOR ALTERING OR CONTROLLING FLOW THROUGH THE PONDS

The phenomena discussed above will allow three general types of flow-control utilizing energy from the natural environment. (A variety of additional things could be accomplished by installing motors and pumps, but these will not be discussed.)

It would be relatively simple to produce a one-way flow in either direction through the inner ponds in the F-series. This is due to the fortunate circumstances that lakes of the adjacent I-series lie quite close to these ponds, and have the tidal characteristics of the local main lagoon. For example, a one-way-gated barrier across the pass between F3 and F4, in combination with a one-way-gated channel from F5 to I3, would produce a unidirectional flushing through F4 and F5. The flow could be set in either direction and would be entirely driven by the tides. Variations on this theme could be used to get many flushing and/or holding possibilities in ponds F3 through F7. Ponds F1 and F2 would be more expensive to control because blocking their wide interconnecting passes would involve much more extensive construction work.

If F6 or F7 were to be included in the tidal flushing scheme, the channel entering each would have to be deepened. This could be desirable, but it might also be useful to leave F6 and F7 in their present state and take advantage of their unusual pattern of evaporation and occasional renewal. This natural flow pattern produces monthly or semimonthly salinity cycles in which salinity may vary by 5 to 10 percent of its mean value. Other periodicities could be achieved by minor alterations of the inlet channels.

A third possibility exists for making use of naturally generated flow. Because of the nonlinear impedance of the F4–F5 channel, the water in F5 is lower than in F4 or I3 during most rising tides—by an amount on the order of

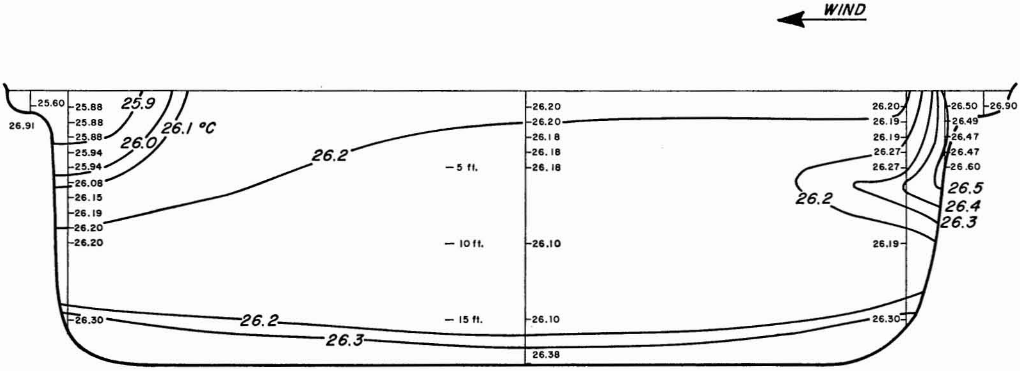

FIG. 4. Vertical temperature section across pond F6. (Section location shown in Fig. 5*a*.)

3 inches. This head difference could be used to produce periodic flows through tanks or small pools constructed adjacent to F5.

INTERNAL STRUCTURE AND CIRCULATION IN F6

Structure

The internal structure and circulation in a single pond were studied to answer certain practical questions:

1. How will nutrients be dispersed in the pond? In particular, will nutrients tend to be trapped in stagnant, lower waters?
2. How would passively floating, brine shrimp eggs be affected by circulation? Can the natural circulation be used to collect them for harvesting?

In general, questions such as these are very difficult to answer in complete detail for natural water bodies. For a body the size of an F-pond, a carefully planned, fully instrumented study lasting several man-weeks would be necessary. In the present case, such time and man power were not available and advance knowledge of the ponds was inadequate for planning a comprehensive study. However, one pond was studied for 3 days with crude techniques. Tentative answers can be offered and, if necessary, a more complete study could now be planned.

F6 was selected for the preliminary survey. It is favorable because of its smaller size and simple shape. By working during a period when tidal effects were absent I was able to study the isolated influence of the wind rather than the more complex patterns that are present if circulation is driven by both wind and tides. This simplification not only increased the chances of discerning sensible patterns during a short survey, but may also have relevancy to actual conditions in an aquaculture operation. Quite possibly certain stages of brine shrimp culture (especially egg production and harvesting) might be conducted in ponds such as F6, which are periodically closed and purely wind-driven.

Fig. 4 is a vertical temperature section roughly aligned with the wind direction; the section location is indicated in Fig. 5*a*. The data were taken in midmorning over a period of about 1 hour. Subsurface readings were made with an instrument of questionable reliability. The device showed serious zero drift, and it was nearly impossible to get good absolute readings. The general nature of the vertical profile at each station was established by repetitive lowerings, and the values at each station were adjusted so that surface temperatures agreed with mercury thermometer measurements. The section is probably roughly correct in its main features, but it does not necessarily present an accurate picture of details or exact absolute temperatures. Independent information about surface circulation was used in locating the intersections of isotherms with the pond surface.

There are four main features of the thermal structure. The bulk of the pond is nearly isothermal. Under the action of the wind, a pool of cooler surface water is accumulated along

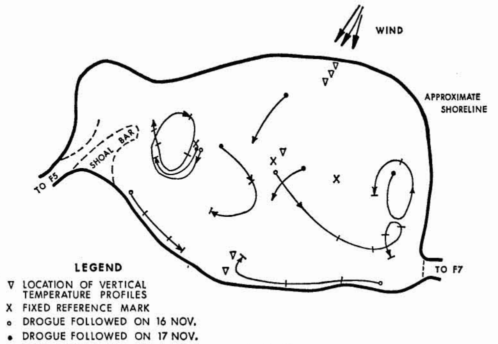

FIG. 5a

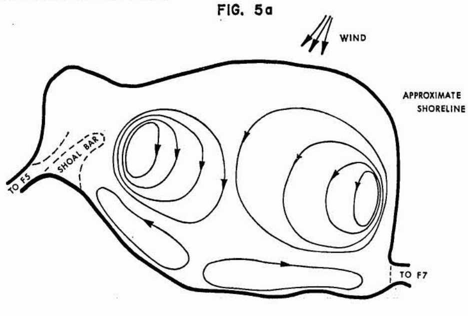

FIG. 5b

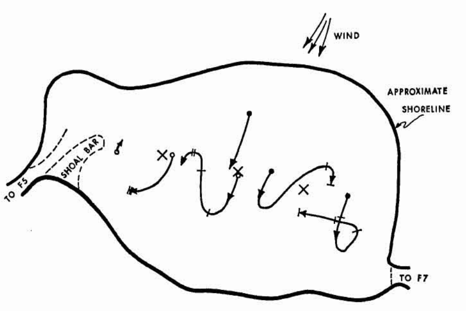

FIG. 5c

FIG. 5. *a*, Tracks of drogues set at a depth of 1 foot in pond F6; *b*, surface circulation in pond F6 as indicated by drogue tracks; *c*, tracks of drogues set at a depth of 5 feet in pond F6.

the leeward shore. Its temperature and position indicate that it must be the least saline water in the pond; its origin is probably the monthly or semimonthly inflow from F5. During the night when the wind slackens, this water probably extends farther upwind over the pond's surface and loses some of the heat it gains by daily warming over the shoal, inshore flats. The amount of this water and its physical properties are probably quite variable in time. Along the shoal shelf adjacent to the windward shore there is also appreciable solar warming and evaporation. This appears to form water of intermediate density which sinks along the bottom and spreads out with mixing at medium depths. The exact extent of the horizontal spreading indicated by the isotherms in Fig. 4 is speculative. The bottom of the deep portion of the pond is overlain by a layer of warmer (and therefore saltier) water which appeared to be less than a foot thick. It is probably renewed (or partially renewed) by the occasional formation of unusually saline water—probably in the windward shoals as discussed above. In connection with this water, we note that most of the pond's bottom, except along the leeward shore, is covered with a thick, pink, gelatinous growth—probably a blue-green algae—which seems to thrive in some of the more saline environments at Christmas Island. The distribution of this algae in F6 tends to indicate the windward shoals as the source of the bottom water. Samples of the algae dredged near the center of the pond smelled strongly of H_2S. It could be that an anoxic condition is produced inside the gelatinous layer (which is several inches thick), or that the thin, bottom layer of water is anoxic. The existence of the warm bottom layer and its possible anoxic condition both indicate that this water is relatively stagnant. Certainly the lowest foot or so of water is not subject to vigorous mixing. However, it is unlikely that a potentially serious "nutrient trap" exists. Even if molecular diffusion is the only mixing process present, a foot-thick bottom layer would have a half-life on the order of 1 week; the bottom layer would lose over half of its excess concentration of any substance within 7 days. So, although the stagnant layer could tie up some of the pond's nutrients, it cannot act as a sink or a permanent trap. (Of course, it would be necessary to minimize nutrient-use by benthic algae, but this would be true whether the bottom layer were stagnant or not.)

The salinities in F6 were above the upper limit of the field instrument (40‰) so distributions of this property were not determined. The temperature data permit some inferences about salinity, and these are presented above.

The temperature section and the structure it indicates are probably roughly typical of all downwind sections except those adjacent to the ends of the pond. The gross features of the structure shown are likely to be present nearly all the time.

Circulation

Currents in F6 tended to be slow and complex in pattern. In this situation, relatively little would be learned from a fixed current meter, and so drogues were used. They were set at 1-foot and 5-foot depths and followed with a skiff. Three fixed markers along the crosswind axis of the pond and natural features on the shoreline were used in estimating the positions of the drogues. Any single position may be incorrect by 100 feet or so, but the overall forms of the drogue tracks are fairly accurate. Figure 5*a* gives the tracks of the surface (1-foot) drogues, and 5*b* is a construction showing an average surface-flow pattern which seems indicated. The wind drives the surface water in two large eddies which have narrow, return flows against the wind at the ends of the pond. This layer of surface circulation extends down less than 5 feet in the central portion of the pond, and to greater depths (probably exceeding 5 feet) toward either end of the pond. In addition, the less dense water along the windward shore seems to move in two elongated eddies as shown. A typical surface current speed is 3 ft per minute.

The drogues set at 5 feet traced the patterns shown in Fig. 5*c*. Generally the currents at this depth are as strong as those at the surface. Unfortunately, nothing more can be done with the subsurface flow than to present the drogue tracks. Whatever is going on is more complicated than the surface flow, and the data are insufficient to allow interpretation.

Two additional points should be mentioned in connection with the pond's circulation. First, freely floating objects having even a small exposure to the air are driven to the leeward shore by the wind. Second, near the end of the observation period, the wind grew stronger than at any time during the study; we estimate its speed at 12 knots. A definite pattern of Langmuir circulation was established over most of the surface of the pond. (In this form of circulation, water particles in the surface layer are driven downwind in paths which are roughly helical. The helixes have axes in the direction of the wind and lying parallel to the water surface. The sense of rotation in the helixes alternates regularly from one to the next, so that alternating bands of surface convergence and divergence are created between them. Foam and floating organic material are collected along the convergences, producing characteristic, parallel "wind slicks.") From the spacing of the slicks observed in F6, we estimate that the Langmuir circulation was stirring the surface layer to a depth of about 3 feet. When this condition is established during strong winds, the horizontal eddies pictured earlier probably cease to exist, and floating objects would be advected toward the leeward shore by the Langmuir cells.

The natural circulation in a wind-driven pond such as F6 could certainly be used in collecting and harvesting shrimp eggs. They would be conveyed to the leeward shore by the direct action of the wind and/or by Langmuir circulation (assuming the eggs float at or near the surface). Under the action of the horizontal eddies that exist during light-to-medium winds, eggs that did not go aground would tend to collect at the convergence near the midpoint of the leeward shore.

ACKNOWLEDGMENTS

Each individual data point in Fig. 3 represents a man walking a quarter-mile or so in the hot sun (or trying to follow a crude path with a flashlight at night), wading thigh-deep into a pond, putting his eye down close to the water's often choppy surface, and reading a gage. Some 450 such trips were made by volunteer helpers from the expedition. The quality of the data proves how well they cared. I am sincerely grateful to the following devoted waders: John Ball, Andrew Berger, Fred Farrell, John Hance, Philip Helfrich, Ed Heald, Mayo Ryder, and Mark Valencia.

I am also indebted to Fred Farrell and John Hance for making drogues and piloting the skiff during the circulation study; they spent long hours cruising search patterns in the hot sun.

Mayo Ryder and John Ball also spent long hours in the sun walking a 2-day level survey of all the tide gages. They produced excellent results, and I thank them.

Last, I want specially to thank two men who helped me the most with getting equipment ready, installing it in the field, and removing it all afterward: Fred Farrell and John Hance.

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